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2
3 THERMO-PHYSICAL OPTIMISATION OF ASPHALT PAVING MATERIALS

4
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ABSTRACT

The paper considers extending the role of asphalt concrete pavements to become solar heat collectors and storage systems. The majority of the construction cost is already procured for such pavements so that only marginal additional costs are likely to be incurred to add the necessary thermal features. Asphalt concretes are, therefore, designed that incorporate aggregates and additives such as limestone, quartzite, lightweight aggregate, copper slag and copper fibre to make them more conductive, or more insulative, or to enable them to store more heat energy. The resulting materials are assessed for both mechanical and thermal properties by laboratory tests and numerical simulations and recommendations are made in regard to the optimum formulations for the twin purposes considered.

INTRODUCTION

Worldwide, asphalt pavement surfacings provide the vast majority of roads, parking lots and airport runways. Given their dark colour, asphalt pavements can heat up to 70°C due to solar irradiation in summertime because of their excellent heat-absorbing properties (1).

Many modern industrial and commercial buildings have a high heating and/or cooling load. This load has a high, potential, environmental impact so there is a strong pressure to obtain the necessary energy from a renewable source. Because such buildings frequently have large adjacent paved areas (roads, vehicle parking lots), there is great potential to collect and/or store solar energy using these adjacent surfaces which are already required and funded for operational purposes (e.g. from a transportation or parking budget). This paper envisages equipping the conventional pavement structure, after making some material adjustments, with fluid-filled pipes resulting in a ‘Thermally Optimized Pavement’ (TOP).

TOPs could be used (Figure 1) either by installing pipes close to the pavement surface, thereby optimizing the pavement to collect solar energy (2) in a Pavement Heat Collection (PHC) configuration, or by installing pipes at the bottom of the pavement in order to use the pavement as a low-grade heat source during winter and as a heat sink during summer in a Pavement-Source Heat Storage configuration (PSHS). Conceivably, the two arrangements could be combined to form a composite system in which solar heat, collected by the pavement surface in the summer, is transferred and stored at shallow depth for subsequent re-use (3). The heat passed to or from the pipes could also be used, directly or via a heat pump, for purposes such as:

- the de-icing of roads in winter,
- the reduction of the Urban Heat Island (UHI) effect,
- to reduce rutting of asphalt,
- to supply hot water,
- or to convert the energy to a transmittable form.

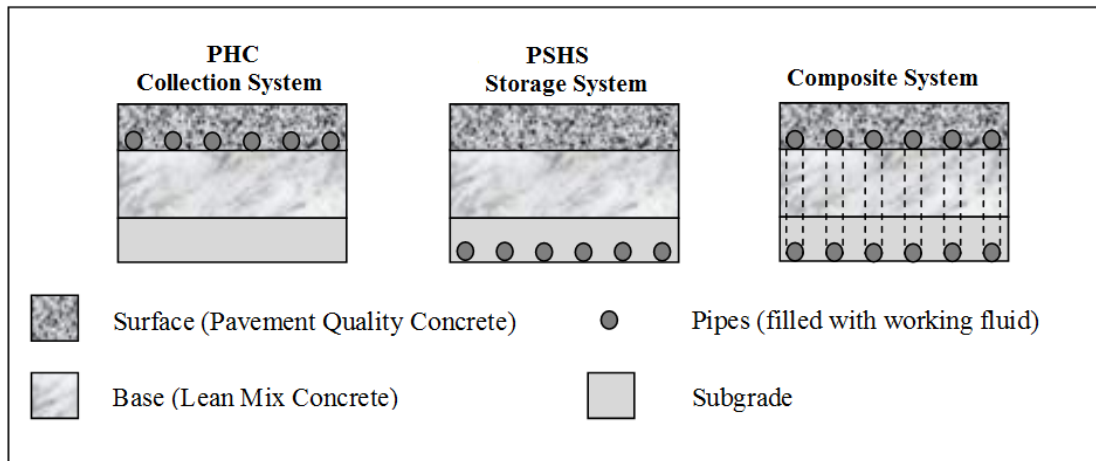


Figure 1 Applications of thermally optimized pavements (Adapted from (4))

OBJECTIVE & SCOPE

To realize the potential benefits of the concept just described, it would be necessary to have pavement materials that continue to provide pavement functionality, but that would also be optimized for their thermal properties. In a companion paper (4) several of the current authors have described the assessment of concrete pavement materials in the application just described. Therefore the objective of this paper is to investigate the optimization and potential for using asphaltic materials for heat storage, transmission and/or insulation while still providing a useful paving function.

EXPERIMENTAL PROGRAMME

A wide range of heavy-weight, light-weight, and normal aggregates, as well as other additives, were considered as potential inclusions within asphalt, being those that might deliver beneficial thermo-physical properties. Those considered were limestone (as reference aggregate), quartzite, sintered pulverised fuel ash lightweight aggregate (known as Lytag®), air cooled copper slag, and copper fibre.

Mix Design

The aggregate gradation and mix design was selected in accordance with the Construction Support Team (5), for a wearing course using macadam concrete, as shown in Table 1.

Table 1 Specification for Wearing Course AC14 (5)

Aggregate Grading	
Sieve Size (mm)	Mass passing given sieve size (%)
14	100
10	77-83
6.3	52-58
2	25-31
1	14-26
0.063	4.5-6.5
Target binder content	Air Voids in Total Mix
4.9±0.4%	4±1.5%
Paving grade of bitumen	
100/150	

93

94 The specifications listed in Table 1 are particularly for limestone, there being no
 95 specification for the other aggregates used in the project. To generate alternative mix designs, the
 96 asphalt mixtures for the other aggregates were generated by replacing the limestone with the same
 97 *volume* of the replacement aggregates while keeping the remaining parameters (bitumen type and
 98 content, and aggregate grading) constant. Due to the non-availability of the larger sizes of Lytag
 99 and copper slag replacement aggregates, two different groups of mixes were produced as follows:

- 100 • Limestone whose nominal size is smaller than 10mm was replaced with
 101 unconventional aggregates (i.e. Lytag, copper slag and quartzite).
- 102 • Two mixes were produced by fully replacing limestone aggregate with quartzite.
 103 One of the mixes in the second group contained about 2% (by volume of the
 104 specimen) copper fibres.

105 Two slabs each, with dimensions of 300mm × 300mm in area and around 60mm thick,
 106 were manufactured for all mixes. The slabs were compacted to the target density using a laboratory
 107 roller compactor. All the slabs were first subjected to thermal testing and then were cored and
 108 trimmed to produce specimens (100mm diameter with mean thickness of 40mm) for the
 109 mechanical test evaluations. The core specimens were, first, subjected to the Indirect Tensile
 110 Stiffness Modulus (ITSM) test which is non-destructive test, next, the same specimens were
 111 subjected to the Indirect Tensile Fatigue Test (ITFT) at different stress levels. In addition, three
 112 specimens (100mm diameter with mean thickness of 40mm) for each mix were also produced in
 113 order to perform the Repeated Load Axial Test (RLAT).

114

115 Mechanical Assessment

116 The Nottingham Asphalt Tester is well-known test equipment which is used to carry out various
 117 performance tests on bituminous materials. It consists of a temperature controlled cabinet

containing a load frame, a sample support and instrumentation cradle, and a loading system comprising a pneumatic load actuator with load cell.

Indirect Tensile Stiffness Modulus (ITSM) test

Stiffness in a pavement material is the principal measurement used to indicate the ability of a material to spread the traffic loading over an area. For comparative purposes a fixed temperature of 20°C was used and the test performed according to the 1993 British Standard (6). The stiffness modulus can be calculated using Equation 1(6):

$$S_m = \frac{L}{(D \times t)} \times (\nu + 0.27) \quad \text{Eq.1}$$

Where

L= the peak value of the applied vertical load (N)

D= the peak horizontal diametral deformation resulting from the applied load (mm)

t= mean thickness of the test specimen (mm)

ν = value of Poisson's ratio, (0.35 for bituminous mixtures)

Indirect Tensile Fatigue Test (ITFT)

Fatigue is the condition whereby a material cracks or fails as a result of repeated (cyclic) stresses applied below the ultimate strength of the material. For the purposes of evaluating the asphaltic specimens in this study, the test was performed according to DD ABF (7) using the stress mode.

The maximum horizontal tensile stress and the maximum horizontal strain for each specimen can be calculated from Equations 2 and 3 respectively.

$$\sigma_{\max} = \frac{2P}{\pi.d.t} \quad \text{Eq.2}$$

$$\varepsilon_{\max} = \frac{\sigma_{\max} \times (1 + 3\nu)}{S_m} \quad \text{Eq.3}$$

Where

P= applied compression load

d= specimen diameter

Repeated Load Axial Test (RLAT)

Permanent deformation is a property that is directly related to the stability of the aggregate skeleton; it being impossible to produce a high deformation-resistant mixture without an appropriate aggregate skeleton. In this study, the repeated load axial test was performed according to the British Standard (8).

Thermal Assessment

Thermal conductivity of the asphalt specimens were determined by the Heat Flow Meter (HFM) technique using a computer-controlled P.A. Hilton B480 that complies with ISO 8301(9). The slab specimens were placed inside the apparatus between a temperature-controlled hot plate and a water-cooled cold plate. More details about the test can be found in previous publications (4). Two slabs were prepared for each mix design, and then the mean value of three independent readings was obtained for each slab specimen.

The specific heat capacity of each mix design was calculated as the sum of the heat capacities of the constituent parts weighted by their relative proportions using a Differential Scanning Calorimetry (DSC) (TA Instruments Model Q10 DSC). The overall specific heat capacity of asphalt can then be calculated from Equation 4:

$$c_p = \frac{1}{w_{total}} \left[w_{Aggregate} \times c_{Aggregates} + w_{Bitumen} \times c_{Bitumen} + w_{Additive} \times c_{Additive} \right] \quad \text{Eq.4}$$

Where

w mass of each constituent in kg,

c specific heat capacity of each constituent in J/kg K.

Thermal diffusivity (α) is the coefficient that expresses the rate of heat energy diffusion (m^2/s) throughout a material when it is exposed to a fluctuating thermal environment and is calculated as:

$$\alpha = \frac{\lambda}{\rho \times c} \quad \text{Eq.5}$$

RESULTS AND DISSCUSIONS

The test results of asphalt mixtures made with the limestone, copper slag, and quartzite are presented and analysed as a group, while the results for LWA are discussed separately.

ITSM Results

Figure 2 shows the mean measured stiffness of all five mixes. Limestone has the highest stiffness modulus value of 2014MPa, followed by copper slag, and quartzite mixtures. The addition of metallic fibre seems to improve the stiffness by about 68% compared to the mix with no fibre (i.e. 100% quartzite mix). Criteria and limits for asphaltic concrete wearing course AC14 with conventional aggregates requires a value for stiffness ranges 1500 to 2000 MPa at 20°C (10, 11). Thus all alternative mixtures perform rather poorly compared with this value.

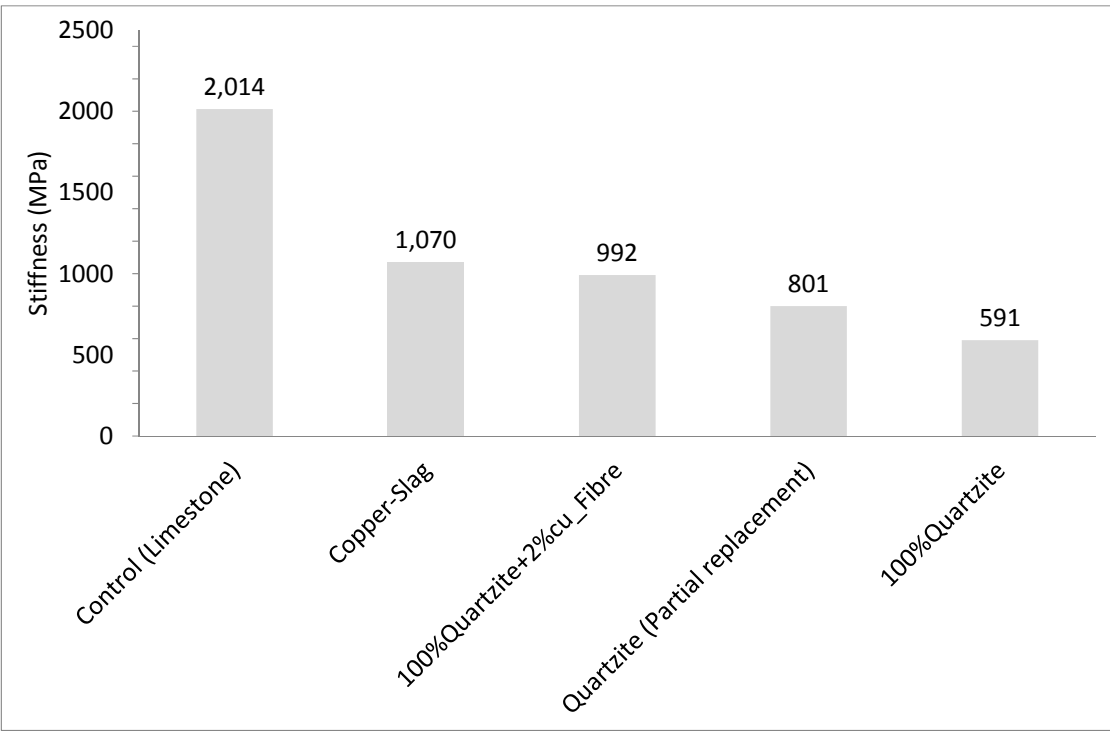


Figure 2 Mean stiffness of different mixtures

Aggregate surface texture was measured using a surface profilometer (2D Mitutoyo Surftest SV 662 profiler). The average readings for five profiles of the roughness (R_a) values for limestone, copper slag, and quartzite were 10.87 μ m, 8.63 μ m, and 5.52 μ m, respectively. The low value for the stiffness of quartzite asphalt may be partly attributable to the relatively smooth faces of the quartzite aggregates as revealed by its low roughness value. The lower ability of quartzite aggregates in absorbing bitumen may also cause the reduction in the stiffness. Since the binder content for all the mixes is the same, lower bitumen absorption could cause a softer mix due to the excess of bitumen. The effect of copper fibres on the stiffness improvement of the mix may be due

to the increased interconnection between fibres, as shown by Figure 3. To produce Figure 3, firstly, 2D cross-sectional images of an asphalt core sample (100mm diameter with mean thickness of 40mm) were produced using a Venlo H 225/350 X-Ray Computer Tomographic (XRCT) scanner at 83 micron resolution and 340 kV accelerating voltage. Then, the 2D image stack was compiled to give a 3D reconstruction.

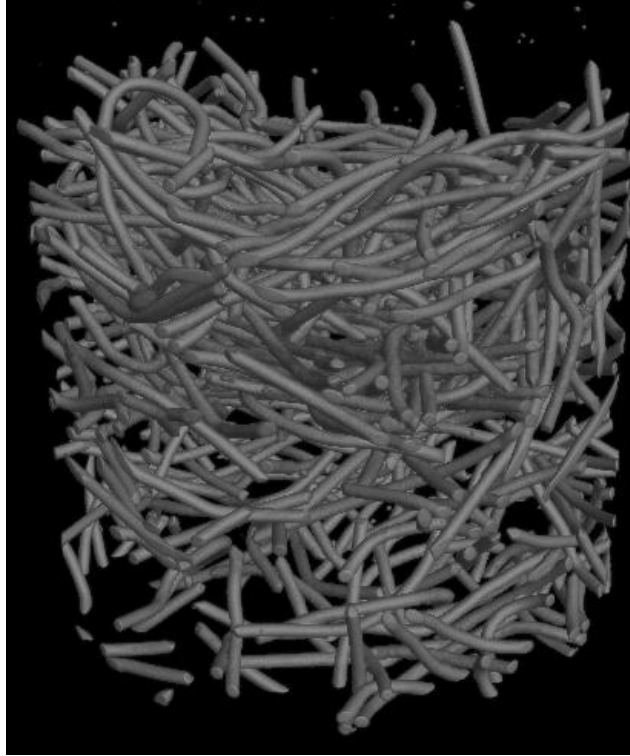


Figure 3 A 3D XRCT images of the formation of copper fibres in the asphalt specimen

ITFT Results

Fatigue life is commonly defined as the number of load cycles to fail the asphalt concrete specimen at a certain stress level. A fatigue regression analysis was performed using the relationship:

$$N_f = k_1 \left(\frac{1}{\varepsilon} \right)^{k_2} \quad \text{Eq.6}$$

where:

N_f Number of Load application to failure;

k_1, k_2 Constants depending on the mixture characteristics;

ε Applied strain;

The fatigue lines are plotted as Figure 4, with the enumerated values of Eq.6 for the five materials given on the figure. The similarity of the values of k_2 reflect the parallel nature of the five lines while the small differences in k_1 reflect the small spacing of the lines with respect to each other. From Figure 4 it can be seen that the asphalt mix containing copper fibre showed the best resistance against fatigue. Both quartzite mixes (i.e. partial & full aggregate replacement) achieved almost the same fatigue line, and the copper slag mix performed slightly better than the limestone mix. The higher fatigue life of the fibre mixture is most likely due to the high level of fibre interconnection observed in Figure 3. Thus all of the unconventional mixtures show a fatigue relationship that is likely to represent satisfactory in-situ performance. Given the lower stiffness modulus of the quartzite asphalt, the greater fatigue life is somewhat surprising. However, a lower stiffness layer would be expected to strain more in-situ for the same level of system loading, so the actual fatigue life might be similar.

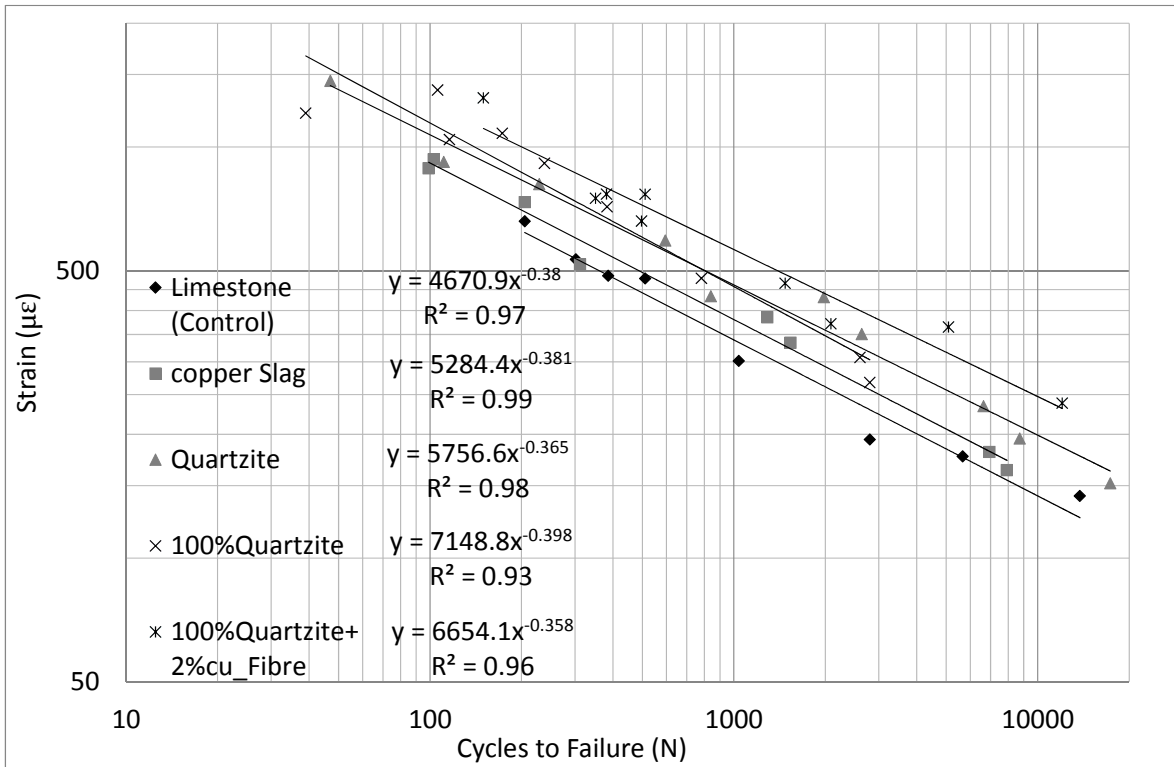


Figure 4 Number of load cycles to failure versus strain

RLAT Results

Figure 5 presents the average axial permanent strain curves obtained from the results of the RLAT tests for the five mix materials. It can be seen that they exhibit a similar response during the loading. The permanent strains all increase rapidly at the beginning, followed by a progressively reducing strain rate per cycle. The deformation occurring in the first 500 cycles is 69%, 69%, 85%,

82% and 83%, respectively for the limestone, copper slag, quartzite (partially replaced), quartzite+2% fibre, and quartzite (fully replaced) asphalts. The quartzite asphalt experienced by far the largest permanent strain. Once again, this could be due to its smooth surface resulting in poor bonding with bitumen.

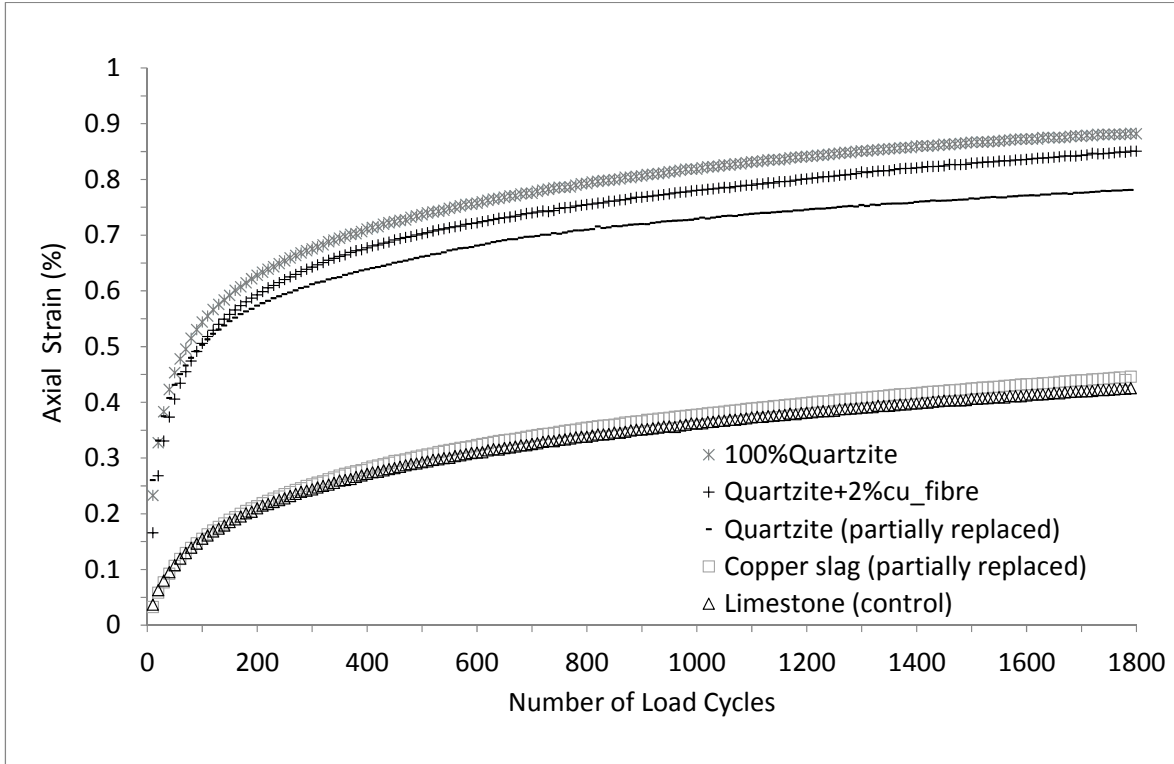


Figure 5 Vertical Permanent Strain Variations with Number of Cycles

Test Results of Thermal Properties

Thermo-physical properties of the asphalt mixtures are presented in Table 2. Table 2 shows that, fully replacing limestone aggregates with quartzite can enhance the thermal conductivity by about 135%. Moreover, the interconnection behaviour of copper fibres (as shown in Figure 3) could further enhance the thermal conductivity by about 14%. However, this increase is unlikely to deliver a significant economic benefit given the typical cost associated with the purchase of copper fibre. Table 2 also shows that, thermal diffusivity of the asphalt mixes reduces due to the reduction of thermal conductivity as well as increase in volumetric heat capacity ($\rho \times c$).

Tests Results of LWA

The slabs generated with LWA were very weak. The aggregates did not bond well with the binder, especially at the corner of the slabs. Due to the poor quality, there were no meaningful results obtained for the ITSM. Two samples were selected and tested under 200kPa and 100kPa for fatigue in order to give a general idea about the fatigue resistance of this mixture. As shown in Table 3, its performance is far behind the other materials. In terms of RLAT, the LWA experienced a deformation of 0.98% in strain, only a little higher than that of the quartzite asphalt. Though it is still the poorest performing, in terms of mechanical properties, it might have a useful role in forming a stabilized sub-base layer. One possibility to improve the performance of LWA could be to increase the binder content, since due to the higher porosity of LWA, a binder content of 4.9% (used in this study) seems not enough to provide an appropriate bond in the asphalt mixture. For thermo-physical properties, one slab was tested and the results are shown in Table 2. The thermal conductivity was approximately half that of the value obtained for the copper slag asphalt, reflecting the potential of LWA asphalt to act as an insulating layer. Given that one would not want to use an insulative layer at the surface of the pavement, but rather just above a lower pipe array (as in Figure 1, PSHS or composite), then the stiffness, fatigue and deformation values would be unlikely to hinder its use at such a depth.

Table 2 Thermo-physical properties of asphalt mixtures

Mix No	Mix type	λ (W/m K)	c_p (J/ kg K)	ρ (kg/m ³)	$\alpha (\times 10^{-7})$ (m ² /s)	Achieved air void (%)
1	Limestone (Control)	1.21	919	2382	5.53	4.1
2	Quartzite (partially replaced)	1.46	880	2351	7.06	4.1
3	Copper slag (partially replaced)	1.05	814	3088	4.15	3.7
4	Quartzite (fully replaced)	2.47	870	2314	12.30	4.9
5	Quartzite +2%Cu-fibre (fully replaced)	2.82	836	2477	13.64	3.7
6	Lyttag (partially replaced)	0.46	863	1504	3.54	4.9

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Table 3: Cycles to failure under 100kPa and 200kPa

	Limestone	Copper slag	Quartzite	LWA
200kPa	915	1289	841	76
100kPa	13781	7924	8728	738

296

297 Numerical Analysis of Thermally Optimized Pavement

298 In order to simulate the relative effects of pavements materials on surface temperature and
 299 temperature depth profile development in the pavements, a one-dimensional finite difference
 300 transient heat transport model (previously validated (12)) was used. The model is accurate to within
 301 2°C variation, and was found to give results at least as accurate as other similar models (13). The
 302 climatic data and pavement section for simulation were extracted from the Seasonal Monitoring
 303 Performance (SMP) conducted under the Long-Term Pavement Performance (LTPP) program (14)
 304 for the state of Arizona, USA. This was chosen as it is a prime location for a PHC installation
 305 where solar radiation exceeds 1000 W/m² in summer, and so representing a ‘best case’
 306 performance scenario. The Arizona LTPP pavement climatic data were collected at weather station
 307 number 0100, between 01/06/1996 to 31/08/1996. The pavement section consisted of a 100mm
 308 wearing course on top of a granular base. Figure 6 shows the predicted surface temperature
 309 variations for two cases;

1) where the pavement wearing course was constructed using limestone aggregates (Mix No.1 (See Table 2) used in the model)

2) where the pavement wearing course was constructed using quartzite aggregates (Mix No.4 (See Table 2) used in the model).

As can be seen from Figure 6, the maximum surface temperature can be reduced when quartzite aggregates are used in the wearing course of the pavement. The maximum surface reduction is approximately 4°C with an average reduction of more than 2°C of the peak temperature. The reduction in surface temperature is because of the higher thermal conductivity of quartzite mix that could increase the rate of heat transfer to the bottom layers of the pavement. Reductions of pavement surface temperature could, potentially, minimise the rutting in asphalt pavements and extend their life. The UHI effect could also be minimised as a result of pavement surface temperature reduction and subsequently air temperature reduction in the adjacent urban area.

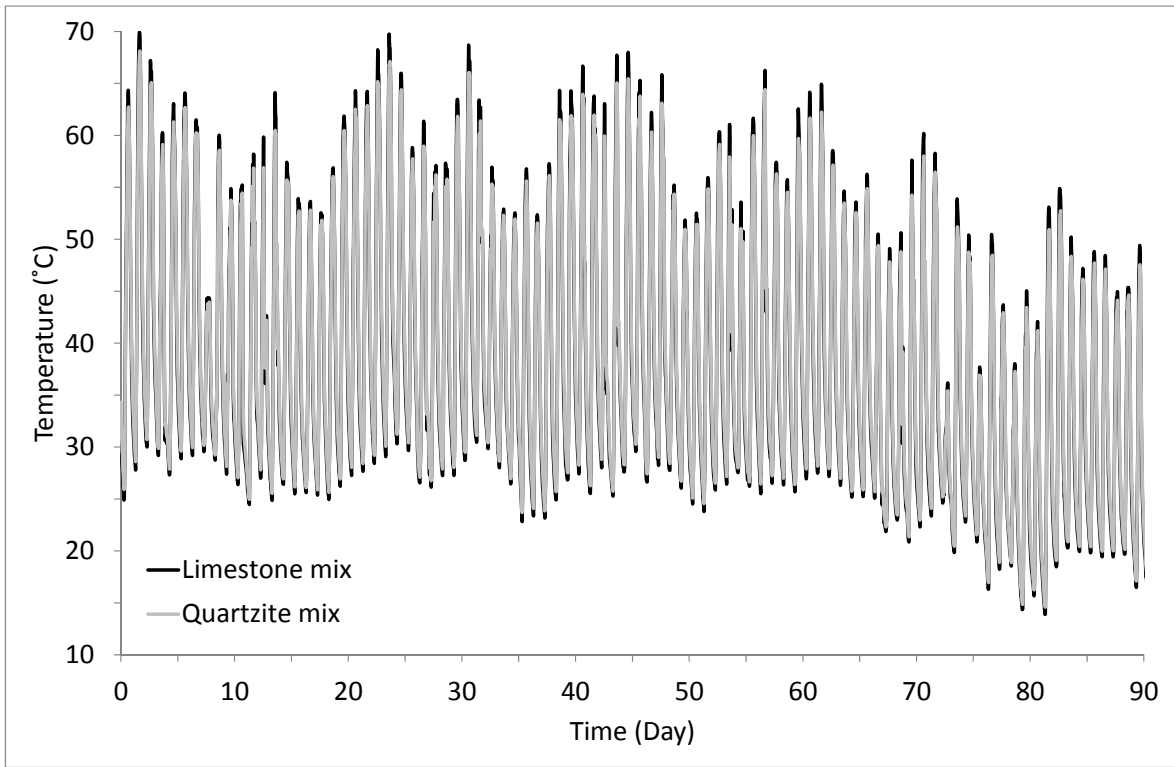


Figure 6 Predicted surface temperatures for limestone (Mix No 1) & quartzite (Mix No 4)

Figure 7 shows the temperature variations at 50mm depth for the two pavements mentioned in above from 01/06/1996 to 01/07/1996 (top) and 01/10/1996 to 01/11/1996 (bottom). Figure 7 shows that using the quartzite mix could increase the average temperature by more than 2°C at 50mm depth in the pavement. This is because a highly conductive surface material facilitates

heat movement within the pavement. This could, potentially, increase the performance of an installed PHC system.

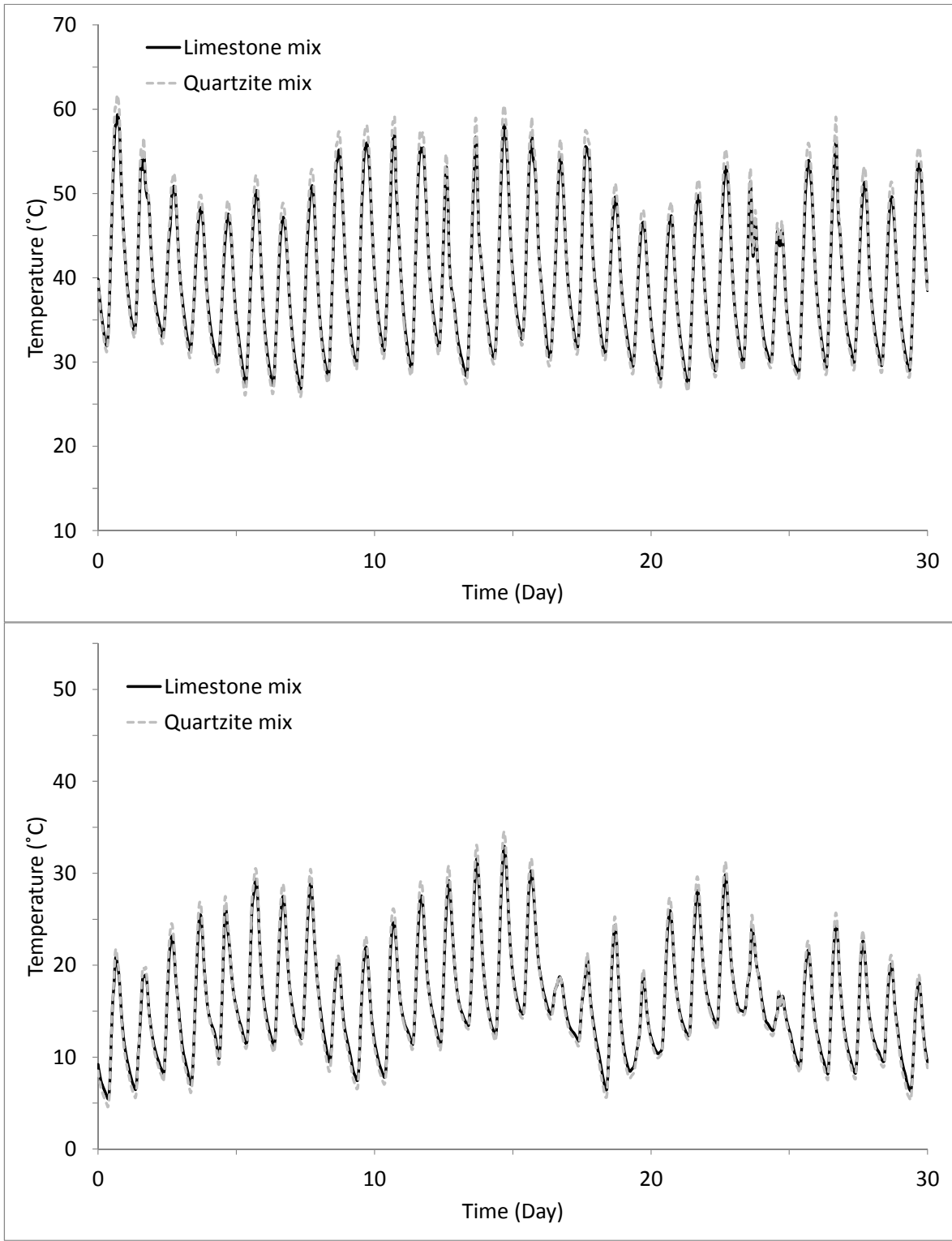


Figure 7 Predicted temperatures at 50mm depth for limestone & quartzite asphalt mixes

339 In order to show the effects of pavement materials on heat storage in the pavement, two
340 pavement cross sections were considered as follows:

341 1) The conventional pavement consisted of 100mm limestone as a surface on top of a 200mm
342 compacted aggregate as a base.

343 2) The modified pavement consisted of 100mm copper slag mix (Mix No.3) on top of a
344 200mm Lytag mix (Mix No.6) as a base.

345 Figure 8 shows the temperature distribution in a typical summer day (top) and winter day (bottom)
346 within conventional and modified pavements. Figure 8 shows that under the modified pavement the
347 temperature remains lower in summer and higher in winter by about 1.6°C. The stable temperature
348 at shallower depth is due to the use of low thermal diffusivity pavement, which can be achieved by
349 using high volumetric heat capacity aggregates and/or low conductivity aggregates. A more stable
350 temperature at shallower depth enabling easier heat storage in the pavement as well as minimising
351 the risk of damage due to freeze-thaw cycling in cold climates.

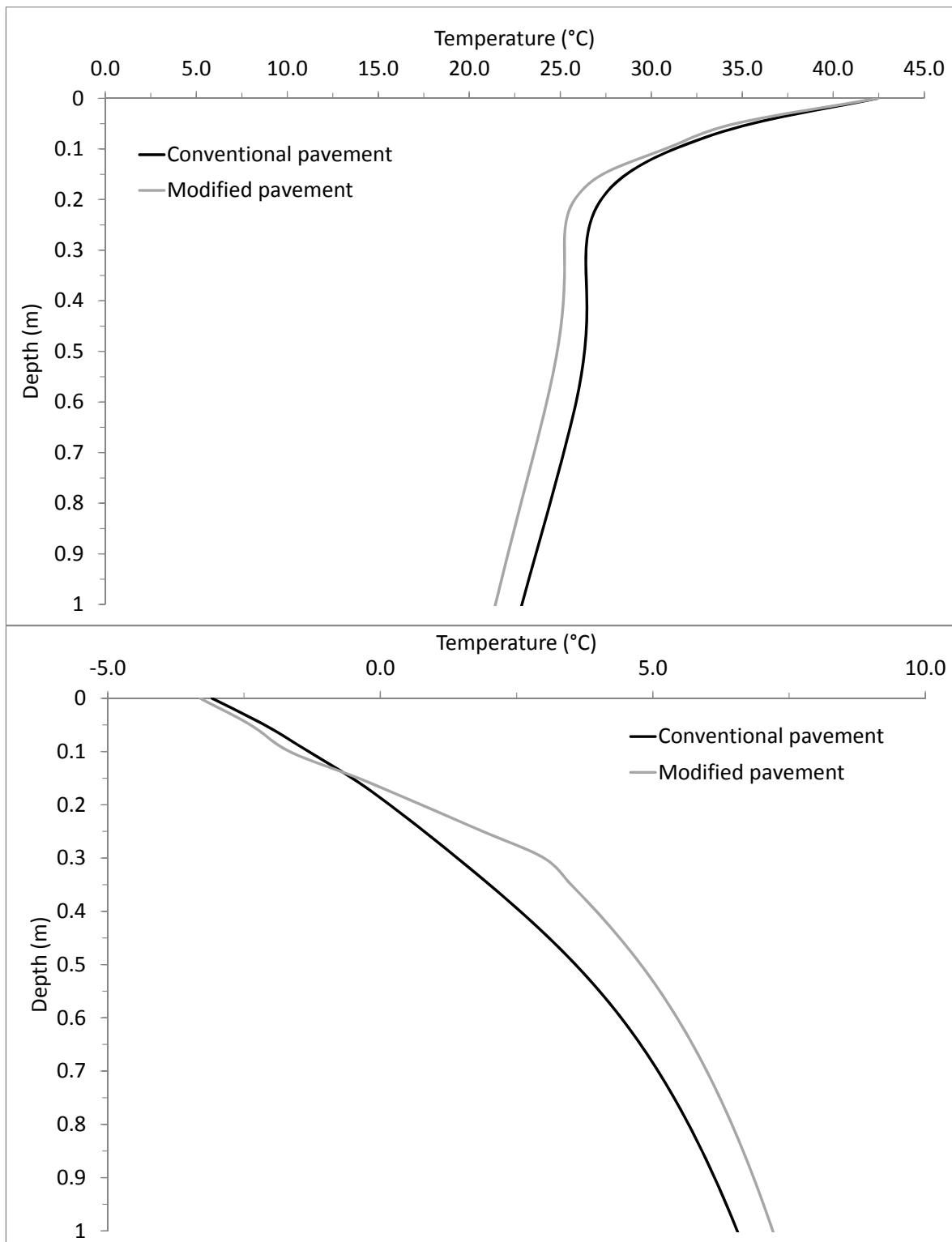


Figure 8: temperature distribution in a typical summer day (top) and winter day (bottom) within conventional & modified pavements.

Mechanical Analysis of Thermally Optimized Pavement

In order to investigate the structural performance of a quartzite asphalt layer (Mix No. 4) compared to a limestone asphalt layer (Mix No. 1), Shell Pavement Design Method software (SPDM) Version

3.0 has been used. The analyses performed with the SPDM were an estimation of the asphalt thickness required to withstand fatigue and rutting under a certain traffic and climate. To take into account the effect of climate, the software requires the monthly mean air temperature for one year and applies correction factors to estimate the resultant temperatures within the asphalt layer. Further adjustment is needed to allow for greater traffic flow at hotter times of the day and for cumulative damage affects. Simplifying considerably, approximate overall correction factors of 1.47 for rutting and 1.92 for fatigue are, thus, applied to mean air temperature (in °C)(15). In order to recognize that the two pavements have different thermal properties, the air temperatures for the SPDM input were calculated by dividing the previously calculated average asphalt temperatures (see Figure 6) by the above factors.

Fatigue simulation

The ITSM tests performed on the limestone and the 100% quartzite mixes have shown that both are not particularly resistant to fatigue (11), hence the pavements simulated were subjected to a relatively low design traffic of one million equivalent standard axles over a design period of 5 years.

Four different structures were simulated namely; Limestone over 200MPa and 800MPa sub-base (L200, L800) and Quartzite over 200MPa and 800MPa sub-base (Q200, Q800). The stiffness value and fatigue line for limestone and quartzite asphalt layers (i.e. Mix No 1 and Mix No 4) were imported to the model from Figure 2 and 4 respectively while other inputs have been kept constant (See Table 4). Comparing simulation L800 and Q800 shows that the limestone mix would need a thickness of 220mm while the quartzite mix would only need 207mm. This is probably due to the fact that, for these first examples, a stiff sub-base is employed which, in the case of the quartzite, might be absorbing most of the stresses. If the stiffness of the sub-base is lowered from 800MPa to 200MPa (simulations L200 & Q200), the limestone asphalt would require a thickness of 400mm against 520mm of quartzite asphalt, which reflects the difference in stiffness.

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Table 4 General inputs for Fatigue & Rutting simulations

Fatigue simulations		Rutting simulations	
Daily Equivalent Standard Axles	400	Daily Equivalent Standard Axles	400
Design Period	5 years	Axle Load	80KN
Lateral Distribution Factor	2	Design Period	5 years
Healing Factor	5	Wheels per Axle	4
Sub-base Thickness	600mm	Contact Stress	570kPa
Sub-base Poisson's Ratio	0.35	Sub-base Thickness	600m
Subgrade Stiffness	150MPa	Sub-base Poisson's Ratio	0.35
Subgrade Poisson's Ratio	0.35	Subgrade Stiffness	150MPa
Mass % of Binder	5	Subgrade Poisson's Ratio	0.35
Volume % of Voids	4	Mass % of Binder	5
Asphalt Poisson's Ratio	0.35	Mass % of Aggregate	95
-	-	Asphalt Poisson's Ratio	0.35
-	-	Bitumen Creep Characteristic Q	0.42
-	-	Bitumen Creep Characteristic B	0.60MPa

399

400

401 Rutting simulation

402 The structures that were obtained from the fatigue simulations have also been investigated from the
 403 rutting point of view, with the addition of two new structures. As can be seen from Table 5, the two
 404 quartzite structures have been given the same asphalt thickness as the limestone structures in order
 405 to isolate the effect of materials on rutting (i.e., since the thicknesses are the same the only
 406 differences observed will be due to the thermal properties of the two materials). These six
 407 structures were simulated by keeping a large number of parameters constant. These general settings
 408 for the rutting simulations are summarised in Table 5.

409 The results from these simulations are shown in Table 5. As can be seen, the quartzite is
 410 constantly performing better than the limestone thanks to its superior thermal properties. Although
 411 a thicker asphalt layer would always be a disadvantage in terms of total rutting compared to a
 412 thinner one, we can see that even in the case of structure Q200, the total rutting still remains lower.
 413 As can be expected, this is even more evident for L800 and Q800 where the quartzite asphalt does
 414 not need to be as thick as the limestone's.

Table 5 Rutting simulations labels and asphalt layer thicknesses

Structure	Thickness (mm)	Rutting depths (mm)
L800	220	21.6
L200	400	25.3
Q800	207	18.8
Q200	520	22.2
New_Quartzite on 200MPa	220	18.2
New_Quartzite on 800MPa	400	23.0

CONCLUSIONS

The study has investigated the desirable mechanical and thermo-physical properties of asphalt concrete pavement materials, their effects on the performance of PHC and PSHS and the implications for mechanical pavement design and performance. The following conclusions can be drawn on the basis of the results and analysis presented in this study.

1. Fully replacing limestone aggregates with quartzite can enhance the thermal conductivity by about 135%. In addition, the quartzite mixture improved the fatigue performance while showing a negative effect on the stiffness.
2. The addition of copper fibre improved the thermal conductivity slightly, while it offered a significant improvement in the stiffness and fatigue performance.
3. The use of LWA and copper slag decreased the thermal diffusivity of asphalt pavements, inducing a more stable temperature at shallower depth which would enable easier heat storage in the pavement as well as lowering the risk of damage due to freeze-thaw cycling.
4. Quartzite asphalt mixes showed the potential to reduce the maximum surface temperature, by up to 4°C. This could, potentially, lessen rutting and the UHI effect, while increasing the performance of the installed PHC.
5. Comparison of the quartzite and limestone wearing courses for their structural performance revealed that the quartzite mix would experience less rutting, however, it would need to be placed thicker so as to compensate for its lower stiffness.

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